PREDICTING SLASH DEPTH FOR FIRE MODELING

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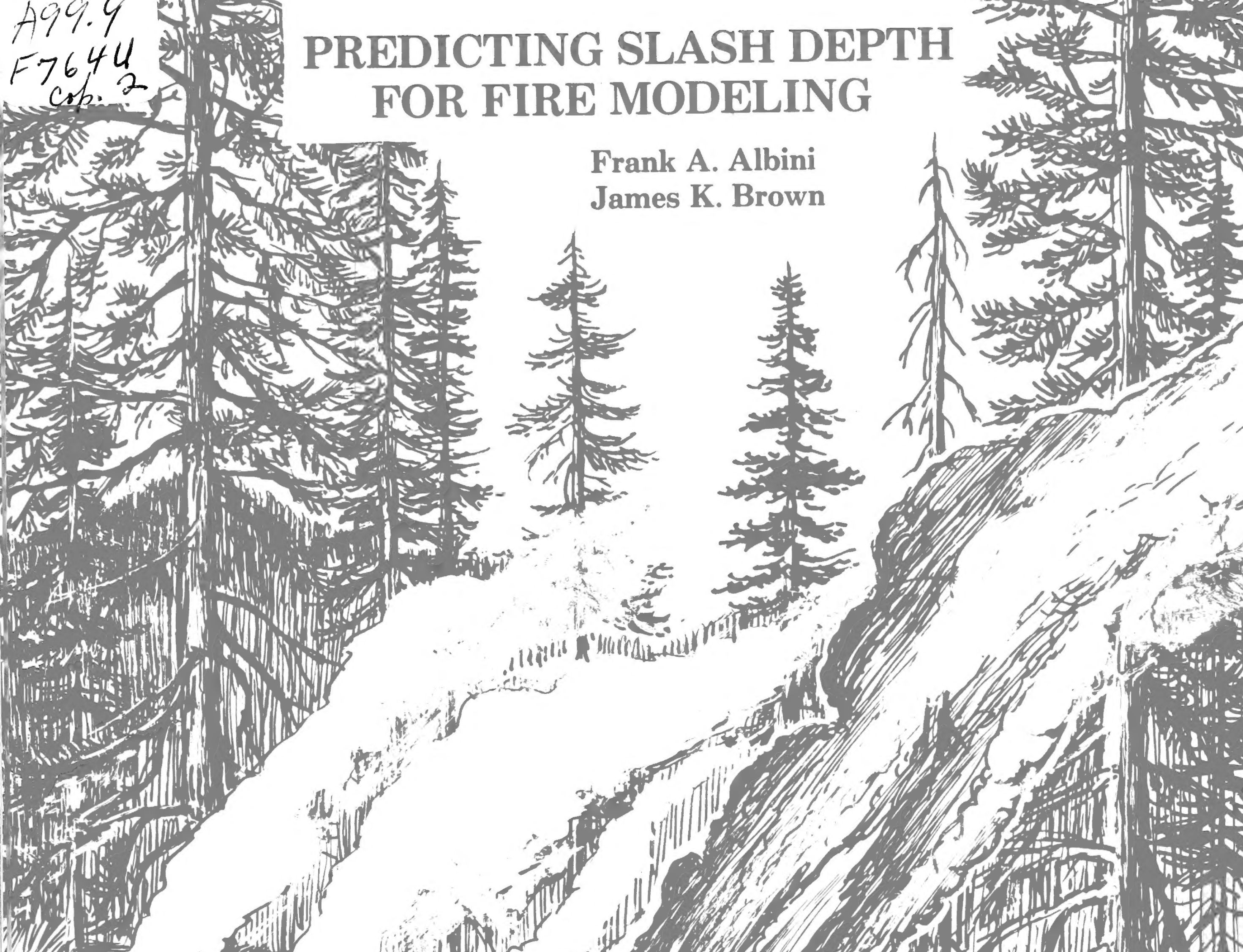

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THE AUTHORS

FRANK A. ALBINI is a Research Mechanical Engineer, assigned to the Fire Fundamentals research work unit at the Northern Forest Fire Laboratory in Missoula, Montana. He earned a Ph. D. from the California Institute of Technology in 1962, where he also obtained his undergraduate training (B. S. 1958, M. S. 1959). He joined the Forest Service in October 1973 after 12 years of pure and applied research and systems analysis both in private industry and at the nonprofit Institute for Defense Analyses.

JAMES K. BROWN received his bachelor's degree from the University of Minnesota in 1960, his master's from Yale University in 1961, and his Ph. D. from the University of Michigan in 1968, all in forestry. From 1961 to 1965 he did research on field measurement of fuel properties and fire-danger rating systems while with the Lake States Forest Experiment Station. In 1965, he transferred to the Northern Forest Fire Laboratory, Missoula, Montana, where he is responsible for research on the physical properties, inventory, and prediction of fuels.

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U.S. Department of Agriculture
Ogden, Utah 84401

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RESEARCH SUMMARY

Development of equations for predicting fuel bed depth (called "bulk depth" herein) appropriate for modeling fire behavior in slash is described. Bulk depth (y) was correlated with the expected number of 1/4- to 1-inch-diameter particle intercepts per foot of vertical plane transect (x) by regressions of the form $y = a\sqrt{x}$. Values of "a" suitable for use in fire models were 0.767 for high-lead harvest debris, 0.940 for precommercial thinning of pines, 1.22 for precommercial thinning in several other western conifers, 0.877 for ground-lead harvest debris in pines, and 0.542 for ground-lead harvest in other species. Lopping of slash reduced average depth 17 percent for harvest debris and 31 percent for precommercial thinning debris. Correlation of high intercept depth (maximum height of sampled fuel particles) with bulk depth showed that the bulk depth can be well predicted using 64 percent of the more easily measured high intercept depth.

Models for settling of slash, retention of foliage and fine twigs, and species mixing, useful in preparing data for fire models, are presented. Application of the models in a slash hazard appraisal computer program is illustrated.

INTRODUCTION

Slash or debris created by harvesting and thinning are a major fire management problem because these residues can create unacceptable fire behavior hazards. Treating slash to maintain an acceptable fire hazard is expensive and requires skillful decision-making. An inexpensive, simple-to-use, yet objective means of appraising the potential fire behavior of slash is needed to aid decisions in managing slash. Knowledge of potential fire behavior can help determine treatment alternatives, the financing of slash treatment activities, and even determine whether the slash should be created. This report describes a method for predicting depth of slash fuels for analytical modeling of fire behavior.

The capability to predict debris and to model fire behavior has made possible a quantitative system for appraising fire behavior potential. Rate of fire spread and flame front intensity can be mathematically modeled using Rothermel's (1972) fire model, which is the basis for computing spread and energy release indexes in the National Fire-Danger Rating System (NFDRS). An area-growth-rate model by Anderson,[1] crown scorch model by Van Wagner (1973), and flame length models by Byram (1959) and Thomas (1962) are also available. A method for assessing total heat release and period of flaming that incorporates large-diameter fuels has been theorized by Albini.[2] The fire models require fuel loading by size class and fuel bed depth as inputs.

Loading and depth of debris vary considerably by cutting prescriptions, therefore must be estimated for each individual cutting situation. Other fuel inputs such as particle density, heat content, silica-free ash content, and particle surface area-to-volume ratio tend to be species dependent and can be approximated from known values (Albini 1976; Brown 1970b, 1974).

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[1]Office memo of August 10, 1973, on file at the Northern Forest Fire Laboratory, Missoula, Montana. (Manuscript in preparation by Hal E. Anderson.)

[2]Albini (1976) outlines the total heat load computation; the computation of burning time is based on empirical work reported by Harmathy (1972) describing structure fires and pile burning, modified slightly to agree with single-particle burning times reported by Anderson (1969).

For Rocky Mountain conifers, loadings of slash can be predicted from relationships between tree crown weight and tree characteristics such as d.b.h. and height (Brown 1978). In the USDA Forest Service Northern Region these relationships have been installed in a computer program that obtains input from tree inventories and predicts potential debris as output.[3,4] In addition to predicting debris, a method to predict fuel depth is needed to appraise fire potential. The objectives of this study were:

1. Determine the relationship between fuel depth and loading of slash and the extent to which species, age of slash, method of skidding, lopping, and other factors influence the relationships.

2. Determine the relationships between the easily measured high intercept depth and bulk depth.

When using analytical models such as Rothermel's (1972), fuel depth is a critical parameter because it determines bulk density of the fuel array for given fuel loadings. Rate of fire spread is very sensitive to bulk density (Williams 1977). Fuel depth is a measure of the vertical extent of fuel in the zone that is actively involved in the spreading flame front. Conceptually, the bottom of this zone is the forest floor and the top is the height where fuel ceases to exist or is too sparse to affect propagation of the flame front. Fuel depth that is compatible with fire modeling can be difficult to measure because locating the top of this hypothetical zone in the fuel array requires judgment.

Fuel depth in slash and other downed woody material has been measured primarily on a high intercept basis (Brown 1974). In this procedure, the top of the fuel is defined by the highest particle to intersect a vertical plane about 1 foot wide. Although this procedure is easy to learn and to use, it does include large void spaces in the fuel array whenever they occur. This permits overestimation of an effective fuel depth and underestimation of bulk density required for fire modeling. A procedure for measuring effective fuel depth--called "bulk depth"--has been developed by William Frandsen (1974) at the Northern Forest Fire Laboratory. It allows observers to account for void spaces in the fuel arrays and provides a measure of effective fuel depth appropriate for fire modeling.

The merchantable top diameter relates to depth. Small top diameters result in more lopping of supporting branches and removal of bolewood than large top diameters; hence, the slash is more compacted. Species may influence depth of slash due to differences in branch stiffness and branching habit. In a study by Roussopoulos and Johnson (1975), loading and depth of slash were directly related; however, as loading increased, depth increased at a reduced rate. Probably as more tree crowns are added to a fixed area, overlapping of branches occurs and the weight may cause compression. Methods of felling and skidding trees should influence depth because the amount of trampling and breakage depends on if and how merchantable boles are removed.

Settling with age has a most significant influence on slash depth. For some western conifers over a 5-year period, depth of lopped and unlopped slash was reduced to one-half of the original value (Fahnestock and Dieterich 1962; Kiil 1968). Rate of settling varied; for some species, depth actually increased slightly during the second year before settling. In a study of piled slash over a period of 29 years, Wagener and Offord (1972) found that piles continued to settle; however, 50 percent of the settling occurred during the first 5 years.

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[3]Users' guide to debris prediction and slash hazard appraisal. 1977. USDA Forest Service Northern Region, Division of Fire Management, Missoula, Mont.

[4]Brown, James K., and Cameron M. Johnston. 1976. Debris prediction system. Office report on file at the Northern Forest Fire Laboratory, Drawer G, Missoula, Mont.

METHODS

Fieldwork

Sampling design.--The study was designed to provide data for four different skidding methods:

1. *Ground lead*.--Crawler tractor and rubber-tired skidder, entire log dragged.
2. *Skyline*.--One end of log elevated.
3. *Helicopter*.--Limited skidding.
4. *Precommercial thinning*.--No skidding.

For each skidding method, two species groups were desired and for each species group, two age classes of slash. For each combination of skidding method, species, and age, we attempted to locate two study sites on areas represented by each of three average loading levels: low (sparsely distributed), medium (nominally about half of ground covered by slash), and heavy (uniformly distributed).

Study sites were located in areas having different loadings to assure that any differences in skidding patterns due to loading would be reflected in the data.

Species were partitioned into the following two groups, based on similarity of lopped depths as observed by Fahnestock and Dieterich (1962):

1. Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco)
   Grand fir (*Abies grandis* (Dougl.) Lindl.)
   Alpine fir (*Abies lasiocarpa* (Hook.) Nutt.)
   Western redcedar (*Thuja plicata* Donn)
   Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.)
   Western larch (*Larix occidentalis* Nutt.)
   Engelmann spruce (*Picea engelmannii* Parry)

2. Lodgepole pine (*Pinus contorta* Dougl.)
   Ponderosa pine (*Pinus ponderosa* Laws.)
   Western white pine (*Pinus monticola* Dougl.)

All slash was at least one-half year old and had existed through at least part of a winter. Two age classes were recognized: 0- to 1-year and 3- to 4-year. Some combinations of skidding, species, and age were not found. Because skyline and helicopter logging has received substantial use only recently in the Intermountain area, the 0- to 1-year and 3- to 4-year lodgepole pine and 3- to 4-year Douglas-fir were unavailable for sampling. Surprisingly, 0- to 1-year precommercially thinned stands other than pines were also unavailable. All other skidding, species, and age combinations were sampled.

Within study areas that were a minimum of several acres in size, two primary transects were established. Along each primary transect, a total of 50 or more sampling points were located at 2-foot intervals. Points without slash were not sampled.

Loading measurements.--Using the planar intersect technique (Brown 1974; Brown and Roussopoulos 1974), loading was measured for at least 15 randomly preselected sample points along each primary transect. Sometimes the random selection resulted in more than 15 points out of 50 for measurement of loading. For 1/4- to 1-inch particles, two 2-foot planes, crossed perpendicularly, were vertically oriented and intersections counted. For 1- to 3-inch and greater than 3-inch pieces, the 2-foot planes were extended to 4 feet. Particles 0 to 1/4 inch were not tallied because of the counting work involved and the fact that the information appeared unnecessary to meet objectives.

Depth measurements.--High intercept and bulk depth measurements were recorded at each sampling point. High intercept depth was measured as the vertical distance from the bottom of the litter layer to the highest 0- to 3-inch diameter slash particle intersecting each 2-foot plane. Pieces greater than 3 inches in diameter were omitted in determining depth because they occur infrequently as the highest particle and have considerably less influence on rate of spread than smaller pieces.

Bulk depth was measured in each of four pie-shaped quadrants of a 2-foot diameter cylinder whose central axis was vertically oriented at each sample point. The two perpendicular sampling planes for tallying intersections of 1- to 3-inch particles, delineated the cylinder into quadrants. The top of fuel was the average height of an imaginary pliable sheet draped over the fuel particles. The bottom was at the base of the litter layer. Vertical gaps free of fuel for more than 1 foot were subtracted from each quadrant's depth. Gaps of less than 1 foot were assumed to maintain vertical continuity of flames, thus were included in the depth measurements. Depths of the four quadrants were averaged to obtain a bulk depth estimate for each sample point.

Lopping.--After loading and depth were measured initially, the slash along the transect was lopped so that all branches were within 2 feet of the ground and boles within 1 foot. High intercept and bulk depths were remeasured at all sample points where depth had changed.

Analysis

Rationale

To understand the rationale behind the method of analysis applied here, bear in mind the objectives of the effort and the nature of the variables. The first objective was to establish an equation that can be used to predict the mean bulk depth of a slash fuel bed from quantities that describe the amount of slash on the area. The sampling procedure provided an estimate of the bulk depth and the variables for quantifying the slash loading at each sample point: the number of intercepts of 1/4- to 1-inch and 1- to 3-inch-diameter fuel particles. The *expected* number of such intercepts can be predicted from slash loading, tree species, and d.b.h. simply by parsing the loading according to the fractional weight distribution of the individual tree crowns (Brown 1978). But the number of intercepts (regardless of size class) is subject to great sampling variability, since it should be approximately Poisson distributed.

A Poisson-distributed variable has a variance equal to its mean, so if N is its expected value, samples from $N - \sqrt{N}$ through $N + \sqrt{N}$ should occur with approximately equal frequency. This intrinsic variability makes it impossible to distinguish with certainty between a change in the mean value of the number of intercepts and simple data scatter when moving from one sample point to the next. To alleviate this problem, the data can be aggregated, combining measurements that lie within a range $\pm\sqrt{N}$ of each other. We can use the average values to discern the underlying trend of the average bulk depth with the average number of intercepts; otherwise, the trend would be largely obscured due to the great scatter in the individual samples. Sampled bulk depths also exhibited significant scatter, indicating a need to aggregate data.

Fuel bed depth was related to the expected number of intercepts of 1/4- to 1-inch-diameter fuel particles per foot of planar intersect by fitting regressions through aggregated data points. The 1/4- to 1-inch particles served as a proxy for the loading of debris fuel under 3 inches in diameter. The fitting of data points resulted from a three-step averaging process as described below:

1. For each study area, the data from the two transects were treated as a single set. Only sample points at which intercepts were counted were assembled in the data set, so the "unit" of sample information consisted of a triplet of numbers--the bulk depth, in inches; the total numbers of intercepts of 1/4- to 1-inch size class fuels in the two crossed sample planes; and the number of intercepts of 1- to 3-inch size class fuels in the same two (extended) planes.

For inspecting these triplets of numbers, they were aggregated and displayed in five categories, according to the number of 1/4- to 1-inch intercepts: 0-2, 3-6, 7-13, 14-22, and 23 or more intercepts. The display (table 1) consisted of the following descriptors for each subset:

a. Average bulk depth
b. Average 1/4- to 1-inch intercept count
c. Number of sample triplets in the subset
d. Mean square bulk depth
e. Mean square 1/4- to 1-inch intercept count.

Scrutiny of such tables quickly revealed sample points that were obviously not representative, so they could be culled from the data set. The mean square depth figures served well to permit the "outlaw" points to be identified. Fewer than 10 points were discarded from more than 1,500 collected.

2. These data were analyzed in many ways in attempting to discover trends and correlations. One fact that soon became evident was that no substantial dependence of bulk depth on the 1- to 3-intercept count could be established, whether or not the 1/4- to 1-intercept count was included. This allowed further simplification by combining data for all 1- to 3-intercept counts. Table 2 displays this simplified data aggregation. An asterisk indicates that a sample point has been discarded in computing the averages shown and two asterisks indicate the discarding of two data points. These data form the basis for the regression relationships between bulk depth and number of 1/4- to 1-inch intercepts.

3. Data in table 2 were grouped by combinations of skidding method, species, and age of slash. Constrained regressions were applied to the data because logically if no 1/4- to 1-inch fuel particles exist there should be no bulk depth. Analysis using unconstrained regressions supported this approach in that the constant terms were small and often statistically nonsignificant.

In deriving the regression equations, the data from all units aggregated were averaged. That is, all the bulk depth-intercept count pairs in the intercept count range 0-2 were averaged, all those in the range 3-6 were averaged, etc. Then the regressions were formed by weighting each resultant aggregate data point by the number of its supporting measurements.

Scatter diagrams of these "grand average" points showed a fraction power law form, so we chose to regress the average bulk depth against the square root of the average number of 1/4- to 1-inch intercepts.

Table 1.--*Sample table of aggregated data from one area used for establishing the relationships between bulk depth and number of particle intersections*

1/4 to 1 intercept count range		Count of intercepts (total) in two crossed 2-foot planes, in 1- to 3-inch diameter size class							
		0	1	2	3	4	5	6	7
0-2	avg. depth	1.433	1.500	2.367	0.	0.	0.	0.	0.
0-2	avg. xcpts	1.333	.500	1.667	0.	0.	0.	0.	0.
0-2	No. points	3	2	3	0	0	0	0	0
0-2	msq depth	2.230	2.500	6.710	0.	0.	0.	0.	0.
0-2	msq xcpts	2.000	.500	3.000	0.	0.	0.	0.	0.
3-6	avg. depth	7.475	1.867	3.050	9.900	0.	0.	0.	0.
3-6	avg. xcpts	4.750	3.667	4.500	4.500	0.	0.	0.	0.
3-6	No. points	4	3	2	2	0	0	0	0
3-6	msq depth	99.57	4.127	9.365	102.4	0.	0.	0.	0.
3-6	msq xcpts	23.75	14.33	22.50	22.50	0.	0.	0.	0.
7-13	avg. depth	4.050	4.833	4.075	3.300	3.433	0.	0.	8.000
7-13	avg. xcpts	10.00	9.333	9.000	12.00	7.667	0.	0.	12.00
7-13	No. points	2	3	4	1	3	0	0	1
7-13	msq depth	21.47	27.08	18.60	10.89	18.43	0.	0.	64.00
7-13	msq xcpts	109.0	91.33	83.50	144.0	59.00	0.	0.	144.0
14-22	avg. depth	0.	6.800	7.150	6.000	0.	0.	0.	0.
14-22	avg. xcpts	0.	15.00	15.00	16.00	0.	0.	0.	0.
14-22	No. points	0	1	2	1	0	0	0	0
14-22	msq depth	0.	46.24	55.75	36.00	0.	0.	0.	0.
14-22	msq xcpts	0.	225.0	225.0	256.0	0.	0.	0.	0.
23+	avg. depth	0.	0.	0.	0.	0.	0.	0.	0.
23+	avg. xcpts	0.	0.	0.	0.	0.	0.	0.	0.
23+	No. points	0	0	0	0	0	0	0	0
23+	msq depth	0.	0.	0.	0.	0.	0.	0.	0.
23+	msq xcpts	0.	0.	0.	0.	0.	0.	0.	0.

TABLE 2.--*Results of partitioning depth and intercept count data by intercept count range. N = number of data points, X = average count of 1/4- to 1-inch intercepts, D = average bulk depth (inches), D^2 = mean square bulk depth (inches^2). Sample units are grouped on the basis of similar types of cutting, species, and debris age. An asterisk, *, denotes deletion of one measurement point, ** denotes two points omitted*

Unit	0 - 2				3 - 6				7 - 13				14 - 22				+23			
number	N	X	D	D^2	N	X	D	D^2	N	X	D	D^2	N	X	D	D^2	N	X	D	D^2
GROUND LEAD HARVEST																				
1975- 2	8	1.25	1.80	3.98	11	4.36	5.58	57.66	14	9.36	4.32	23.48	4	15.25	6.78	48.43				
1975-11	3	1.33	2.50	8.42	11	4.45	5.03	36.48	13	9.54	11.28	170.7	6	15.83	11.73	161.7	2	35.00	16.80	282.5
1975-13					3**	5.00	2.93	10.96	16	10.69	12.87	259.8	7	17.43	11.93	157.1	4	31.75	14.83	234.7
1975-14	3	.67	3.70	25.21	8	5.00	6.28	44.85	9	9.78	8.24	84.30	11	16.73	23.20	785.1	1	32.00	16.30	265.7
1975- 7	4	1.25	3.40	13.62	9	4.11	7.36	80.51	13	8.77	11.94	219.9	5	14.80	17.00	366.8				
1975- 8					1	6.00	3.80	14.44	16	9.25	7.19	74.53	5	16.20	10.52	122.8	13	38.31	17.88	381.0
1975- 9	1	2.00	2.30	5.29	3	4.67	3.67	16.33	16	11.06	11.88	192.8	11	17.55	17.38	329.9	4	29.00	15.08	303.3
1975-10					4	5.00	6.40	51.65	22	10.55	8.76	99.14	8	16.88	9.90	103.4				
1975-12					1	4.00	2.00	4.00	14	10.50	12.30	190.0	15	17.20	13.76	224.9	6	26.83	19.85	477.3
1975- 3	8	1.00	2.64	8.82	12	4.33	4.63	32.44	12	8.75	17.83	374.4								
1975- 5	2	2.00	3.40	12.77	17	5.00	4.25	28.75	17	8.94	7.92	89.03	1	22.00	16.00	256.0	1	32.00	29.00	841.0
1975-23	20	1.20	1.92	6.32	12	5.00	3.56	21.98	5	8.40	6.28	59.14								
1975-24	13*	1.54	4.56	28.41	21	4.57	7.33	67.97	2	7.00	6.30	39.69								
1975-25	3	.67	2.17	4.75	19	4.63	6.72	60.88	11	8.36	11.99	175.2	1	14.00	30.30	918.1	1	25.00	26.8	718.2
1975-26	3	1.33	4.27	20.78	22	4.82	8.08	80.51	9	9.11	10.17	126.5	1	16.00	9.00	81.00				
1976-3	8	1.50	1.80	4.05	11	4.18	2.70	9.15	9	8.11	5.92	40.90	5	15.60	12.88	173.7				
1976-4	5	1.00	2.22	6.49	11	4.00	5.62	39.05	15	8.60	7.86	72.94								
1976-23	7	1.71	3.13	12.05	9	4.44	6.83	56.33	13	8.69	12.75	223.9	2	16.00	21.75	512.1				
1976-24	4	1.50	4.38	47.06	10	4.80	7.23	85.75	8	9.50	17.24	434.4	8	17.00	22.28	566.0				
1976-30	1	2.00	1.50	2.25	8	4.50	5.11	39.81	19	10.53	14.14	285.6	4	15.25	19.95	484.6				
PRECOMMERCIAL THINNING																				
1975-15	3	1.67	2.27	7.25	6	4.17	3.57	14.74	25	8.76	19.32	439.7	2	14.50	21.25	469.6				
1975-16	3	2.00	3.20	10.86	5	4.80	12.42	208.9	18	9.83	14.62	266.6	13	16.69	12.02	186.4	2	23.00	14.15	202.0
1975-17	10	1.10	6.78	81.87	8	4.50	6.85	75.78	12	8.83	13.12	204.2	1	14.00	13.80	190.4	1	32.00	5.80	33.64
1975-18	1	1.00	6.50	42.25	9	4.56	17.42	336.2	17	9.53	22.56	616.5	9	18.00	22.03	594.3	3	30.33	24.47	785.7
1976-10	5	1.20	3.88	26.58	16	4.75	5.32	42.88	13	7.38	7.62	68.92					1	27.00	28.50	812.3
1976-12	2	1.50	1.30	16.90	10	4.20	4.57	29.48	12	9.33	9.53	132.8	7	17.14	12.81	202.7	1	25.00	23.00	529.0
1976-13	5	1.40	2.84	22.21	10	4.40	10.26	146.5	10	9.00	7.82	76.62	3	19.67	13.70	211.2	2	23.50	11.80	140.2
1976-15	3	1.67	3.63	13.59	9	4.44	4.86	32.35	19	9.47	14.25	254.7	3*	14.33	11.63	137.1				
1976-16	4	1.75	5.98	47.02	17	4.65	8.84	117.0	13	9.31	15.59	278.4					1	23.00	22.80	519.8
1976- 1	11	1.27	3.65	18.80	9	4.56	11.01	210.0	12	8.58	18.21	427.8	2	15.00	20.15	558.5				
1976- 5	11	1.18	4.75	34.83	14	4.50	13.36	227.9	11	8.55	15.28	338.9	2	15.00	16.65	280.6				
1976- 6	1	2.00	9.50	90.25	10	5.00	12.03	163.4	20	9.80	17.70	344.5	3	15.67	20.93	447.8				
1976-17	13	1.08	4.16	24.86	11	4.09	8.10	85.35	9	8.67	10.91	128.2								
1975- 4	2	.50	11.65	157.3	6	3.83	13.13	241.0	15	9.20	14.41	255.6	8	18.00	21.25	551.3	3	27.33	31.20	101.9
1975-19	1	2.00	5.00	25.00					13	10.23	13.66	242.8	17	16.82	19.95	453.9	3	23.67	30.63	999.1
1975-22	12	1.42	1.88	3.99	26	4.12	3.33	15.80	4	7.75	6.98	69.32	1	14.00	7.50	56.25				
1976- 9	14	1.43	2.84	15.30	6	4.50	8.23	107.9	6	9.33	15.37	292.0	4	16.75	21.30	474.8				
1976-27	2*	1.43	5.40	45.97	11	4.36	13.64	260.3	16	10.06	17.94	350.6	3	16.33	13.63	188.3				
1976-28	2	2.00	5.80	34.64	5	5.20	17.72	316.2	14	11.36	23.84	594.8	11	15.73	20.73	492.2	1	25.00	37.5	140.6
1976-29	16*	1.12	5.83	42.20	11	4.45	9.26	97.48	2	8.50	8.25	68.13								
1976-31	6*	1.17	7.47	98.76	17	3.88	13.04	192.6	6*	8.33	15.43	250.9								
HIGH-LEAD HARVEST																				
1976-18	2	2.00	5.40	35.92	9	4.89	9.70	120.4	17	9.12	13.59	222.5	1	14.00	6.80	46.24				
1976-20	5	1.00	3.62	15.85	12	4.42	9.13	134.8	14	9.86	13.87	290.6	3	16.00	20.27	533.0				
1976-21	6	1.33	3.27	15.16	9	4.33	8.44	164.6	10	10.00	17.52	429.3	5	17.00	28.58	864.0	1	24.00	38.50	148.2
1976-26	3	1.00	4.60	22.45	13	5.00	9.97	140.1	13	9.00	15.48	308.4	2	15.00	13.25	208.6	3	29.00	23.27	599.2
1976-14	3	1.33	8.03	98.94	6	3.67	14.45	305.1	6	9.00	15.93	329.2								
1976-19					8	4.13	9.53	129.7	12	8.67	13.38	206.8	3	14.00	12.27	154.8				
1976-22	6	1.83	2.77	9.51	14	4.29	4.68	29.35	9	9.11	7.08	54.85	1	19.00	14.80	219.0	1	23.00	6.50	42.25
1976-25	2	1.00	2.00	4.25	7	4.29	5.30	51.40	18	9.44	10.01	131.5	5	15.00	10.62	125.1				
1976-35	3*	1.00	5.78	39.31	9	4.11	10.62	167.0	11	9.18	17.79	395.9	4	17.25	24.40	610.5	3	26.33	21.27	568.3
1976-36	1	1.00	4.50	20.25	8	4.88	4.38	24.38	17	10.00	13.48	206.3	3	15.00	22.20	520.3	2	42.50	21.50	468.5
1976-37	4	1.50	4.08	25.37	4	5.25	7.90	90.92	11	10.45	18.35	430.6	8	18.13	22.10	552.3	4	28.75	24.10	614.7
1976-38	3	1.67	4.93	27.51	13	4.38	6.05	58.07	7	9.57	11.57	188.4	5	19.00	13.08	185.1	4	28.25	21.18	457.9
1976-39	4	2.00	4.65	27.65	8	5.25	7.13	85.75	3	9.67	19.00	369.7								

One penalty for using constrained regressions is that there is no widely accepted simple quantity that reflects the degree of agreement between the equation and the data, in the way that the "coefficient of determination," called r^2, does for unconstrained regressions. If y_i represents a bulk depth data point to be fitted by regression, $\hat{y}_i$, the value of the bulk depth predicted by the regression expression, and $\bar{y}$ the average of the data points to be fitted, then, by statistical theory the expression for the coefficient of determination for a constrained regression should be

$$r^2 = 1 - \Sigma(y_i - \hat{y}_i)^2/\Sigma(y_i^2).$$

This quantity is, however, a poor measure of the "goodness" of the regression equation. So we have used, in this presentation, a nonrigorous but intuitively more appealing measure of the suitability of the regression description:

$$s = 1 - \Sigma(y_i - \hat{y}_i)^2/\Sigma(y_i - \bar{y})^2.$$

This parameter compares the variance about the regression to the variance about the mean, as does "r^2" for an unconstrained regression, but it is not limited numerically to the range 0 to 1. It is restricted only to be less than unity, and can be negative.

RESULTS AND DISCUSSION

Depth Versus Intercept Counts

Regression results for all of the skidding, species, and age combinations obtained in the study are shown in table 3. The relationships for skyline and helicopter skidding were similar; so they were combined and called "high-lead." The high values of the fit descriptor, s, are largely due to the manner of aggregating data. Examples of fit are shown in figures 1, 2, and 3. Because of the data aggregation, tests for differences among the slash groups seem irrelevant. However, recognizing the large amount of variation among sampling points and the similarity of some of the regressions in table 3, the equations in figure 4 are recommended for application to fire modeling. To obtain the equations for initial depth shown in figure 4, some of the results in table 3 had to be adjusted to age 1 year.

Merchantable top diameter limits and d.b.h. of trees thinned precommercially appear to significantly influence the depth-intercept count relationship. We were unable to include a wide range of conditions for these factors; thus, application of our results should be restricted to conditions similar to ours. Applicable conditions include merchantable top diameters of 4 to 6 inches for pine and 5 to 6 inches for other species, and precommercial thinning of trees 2 inches and greater in d.b.h.

TABLE 3.--*Constrained regressions through aggregated data points relating average bulk depth, y (inches) to average number of intercepts of 1/4- to 1-inch debris fuel in two-crossed 2-foot sample planes, x*

Type of cutting	Dominant species	Age of debris (year)	Sample included for data averaging: Year	Units	Regression results: Equation	"S"	Figure reference
Ground-lead harvest, 6-in top	DF, mix	1	1975	2, 11, 13, 14	$y = 3.16\sqrt{x}$	0.86	
Ground-lead harvest, 6-in top (slashed after harvest removed)	DF	2, 3	1975	7, 8, 9	$y = 3.22\sqrt{x}$	.87	
Ground-lead harvest, 6-in top (slashed after harvest removed)	DF	1	1975	10, 12	$y = 3.18\sqrt{x}$	.86	
Ground-lead harvest, 6-in top	DF	3	1975	3, 5	$y = 3.45\sqrt{x}$	.71	
Ground-lead harvest, 3-in top	LP	1, 3	1975 1976	23, 24, 25, 26; 3, 4	$y = 3.03\sqrt{x}$	.88	
Ground-lead harvest, 6-in top	DF, mix	1,2,3	1975	2,3,5,7,8,9,10,11,12,13,14	$y = 3.27\sqrt{x}$	.93	3
Ground-lead harvest, 5-in top	LP	1	1976	23, 24, 30	$y = 4.51\sqrt{x}$	.84	
Precommercial thinning	PP	4	1976	10, 12, 13, 15, 16	$y = 3.56\sqrt{x}$	.92	
Precommercial thinning[1/]	LP	4	1976	1, 5, 6, 17	$y = 5.22\sqrt{x}$	.98	
Precommercial thinning	DF	3, 4	1975	4, 15, 16, 17, 18, 19, 22	$y = 4.75\sqrt{x}$	.90	1
Precommercial thinning	LP, PP	1	1976	9, 27, 28, 29, 31	$y = 5.58\sqrt{x}$	.94	
High-lead harvest, 6-in top	Mix	1	1976	18,20,21,26,35,36,37,38,39	$y = 4.60\sqrt{x}$	.91	2
High-lead harvest, 6-in top (lopped by harvest crew)	Mix	1	1976	14, 19, 22, 25	$y = 3.60\sqrt{x}$	.96	

[1/] These units are not typical of current practice, as trees of large d.b.h. were thinned. The relationship developed was not used for model purposes for this reason.

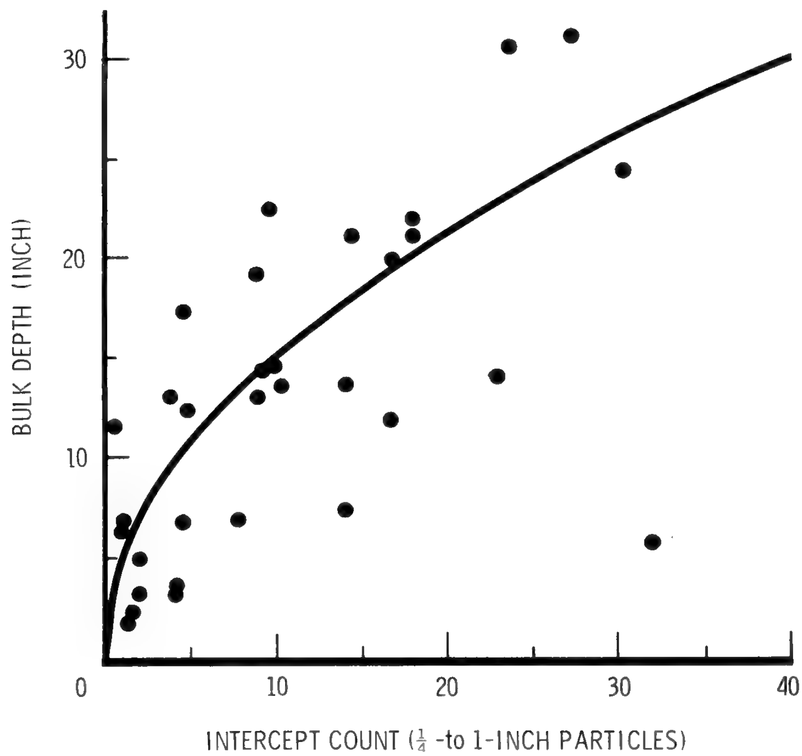


Figure 1.--Aggregated data for bulk depth as a function of intercept count (1/4- to 1-inch particles per 4 feet of transect) for precommercial thinning. Analysis is shown in table 3.

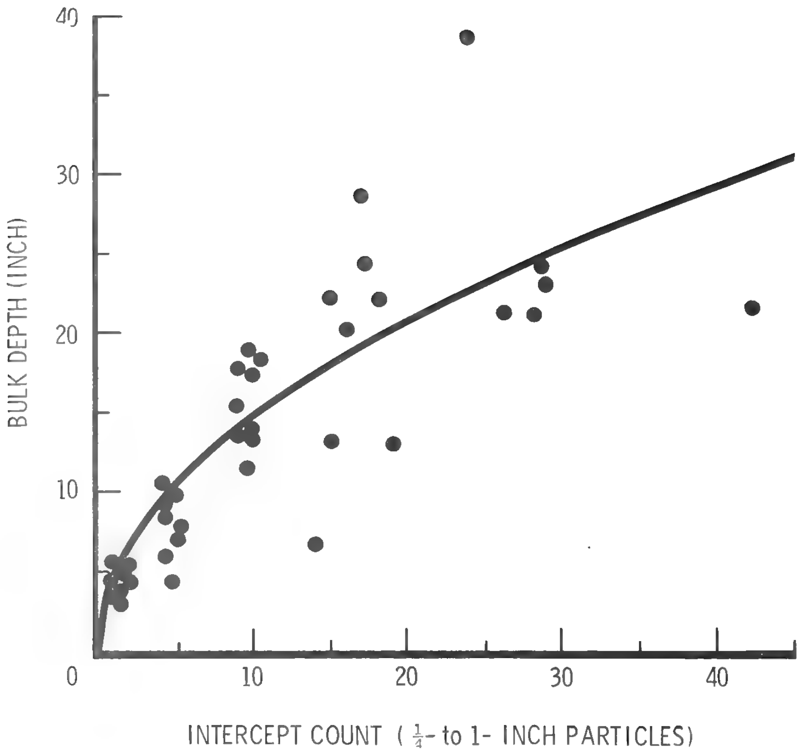


Figure 2.--Aggregated data for bulk depth as a function of intercept count (1/4- to 1-inch particles per 4 feet of transect) for high-lead skidding. Analysis is shown in table 3.

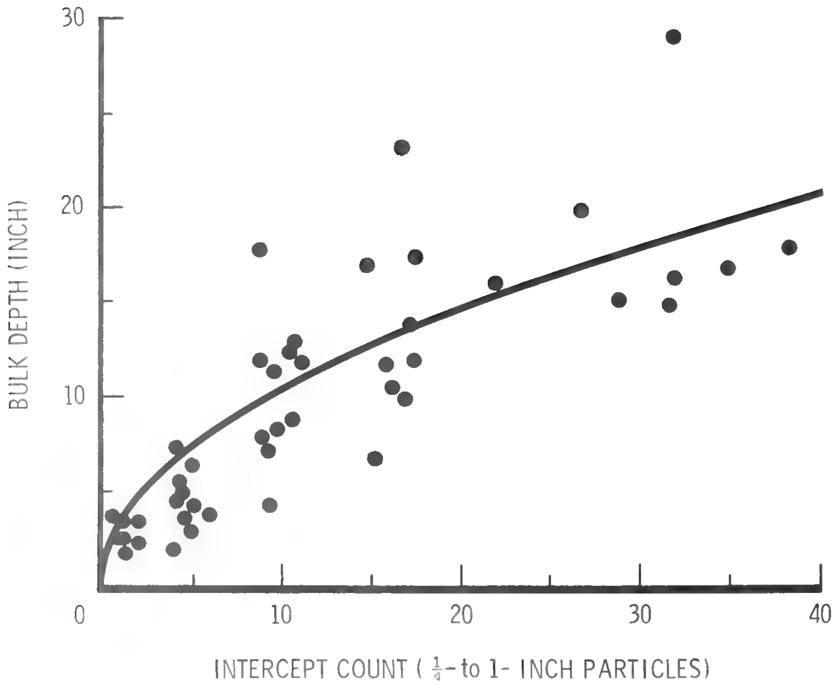
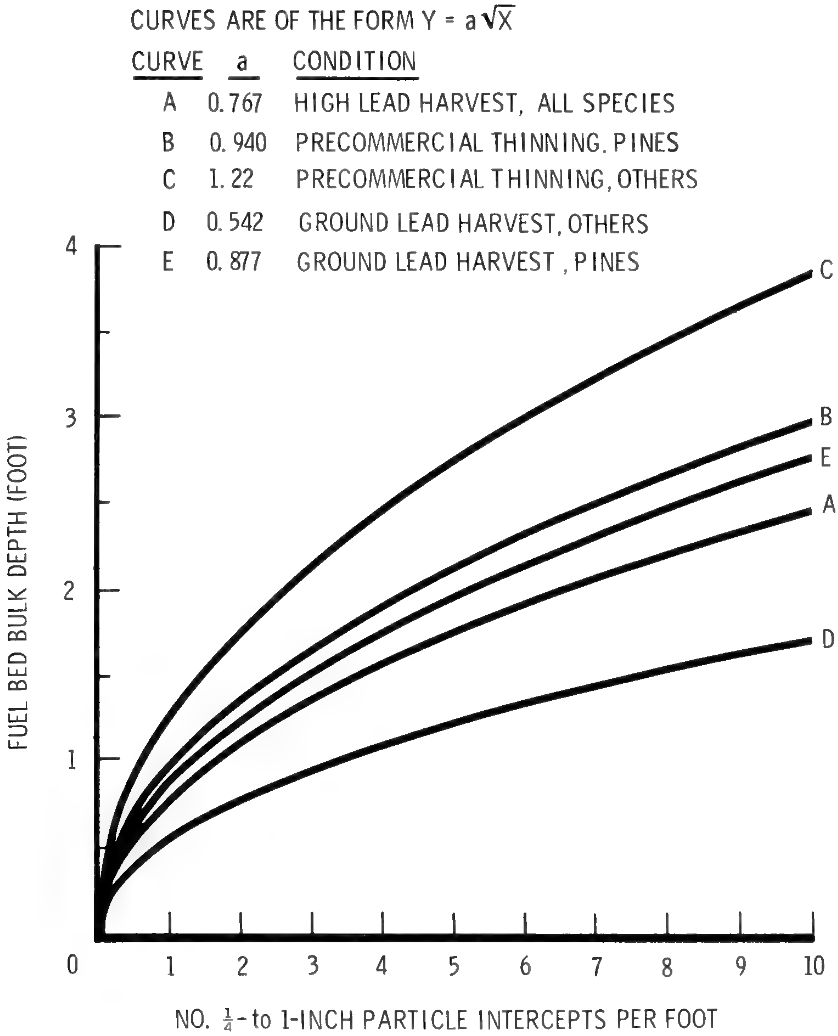


Figure 3.--Aggregated data for bulk depth as a function of intercept count (1/4- to 1-inch particles per 4 feet of transect) for ground-lead skidding. Analysis is shown in table 3.

Figure 4.--Relationships between fuel bed bulk depth (first year) and expected number of intercepts per foot of transect for modeling fire behavior in slash.



Bulk Depth Versus High Intercept Depth

Measurement of bulk depth is time consuming and subject to personal interpretation. However, the simpler to measure "high intercept depth" (Brown 1974) tends to underestimate fuel bed compactness, resulting in a systematic overestimation of the rate of fire spread and reaction intensity by Rothermel's (1972) model (Brown 1972; Bevins 1976; Hough and Albini 1978). But because it is rapid, reliable, and widely used, we determined the regression relationship between high intercept depth and bulk depth to provide a formula that can be used to reduce the high intercept measurements for use in the Rothermel fire spread model. The analysis was made on pairs of bulk depth and high intercept depth measurements taken at each point.

Examination of a large number of regressions for various combinations of skidding, species, and age revealed no substantive differences between the regression coefficients.

Also, all the regression lines passed very nearly through the origin. For example, treating all debris of age 2 years and less as one set and all debris older than 2 years as another set gave the following relationships:

$$\text{AGE} \leq 2\text{: } y = -0.0245 + 0.661X \qquad (r^2 = 0.78)$$
$$\text{AGE} \geq 2\text{: } y = 0.303 + 0.602X \qquad (r^2 = 0.74)$$

where

y = bulk depth (inches)

x = high intercept depth (inches).

Variation among regression coefficients was restricted as shown by the histogram of ratios of bulk depth-to-high intercept depth computed for 118 transects (fig. 5). Sixty percent of the ratios were between 0.55 and 0.75. Regression coefficients pertaining to the major skidding, species, and age groups are shown in table 4. Variability of coefficients within slash groups is comparable to variability among slash groups. Thus, the narrow range of variability and probable difficulty in establishing significant differences among slash groups seems to warrant application of one relationship between bulk depth and high intercept depth to all slash. Combining all measurements produced the regression:

$$y = 0.638X$$
$$(s = 0.76)$$

which simply states that bulk depth is 64 percent of high intercept depth. This compares with 52 percent observed by Bevins (1976) in studying Douglas-fir and hemlock slash in Washington.

Interestingly, the finding of 64 percent is consistent with fire spread verification studies (Brown 1972; Bevins 1976; Hough and Albini 1978) in which fuel bed depths that were reduced by factors in the range of 0.6 to 0.7 improved fire spread predictions by the Rothermel model.

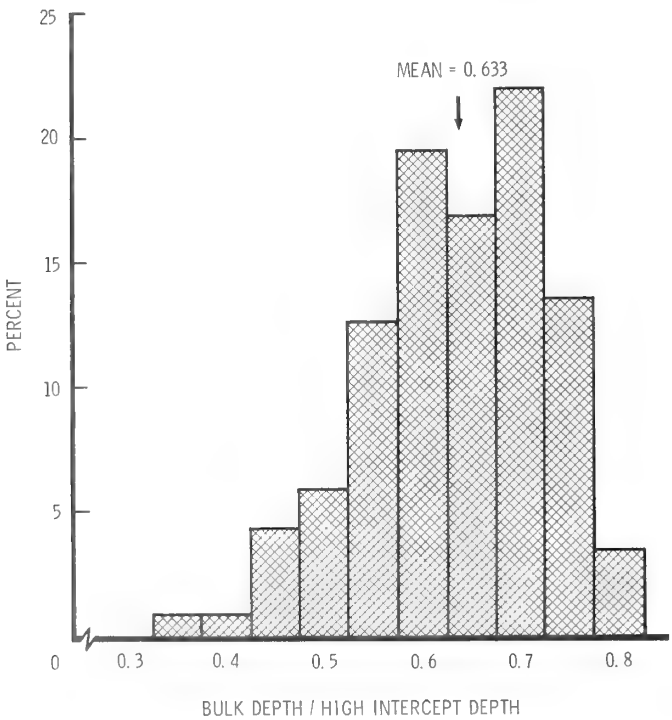


Figure 5.--Histogram of regression coefficients for the constrained relationship between bulk depth versus high intercept depth determined for individual transects.

TABLE 4.--*Constrained-regression coefficients (b = ratio of bulk depth to high-intercept depth) for skidding, species, and age groups*

Type of cutting	Dominant species	Age of debris (years)	Areas included	b-coefficient Average	Standard deviation
Ground-lead harvest	DF	0-1	1975-2,10,11,12,13,14,20	0.610	0.030
Ground-lead harvest	DF	3-4	1975-3,5,7,8,9	.599	.031
Ground-lead harvest	LP	3	1975-23,24,25,26	.596	.079
Ground-lead harvest	LP	1	1976-3,4,23,24,30	.698	.036
Precommercial thinning	PP	4	1976-10,12,13,15,16	.592	.107
Precommercial thinning	LP	3-4	1976-1,2,5,6,7,17	.653	.066
Precommercial thinning	DF	3-4	1975-4,15,16,17,18,19,21,22	.575	.092
Precommercial thinning	PP	1	1976-9,11,27,28	.713	.059
Precommercial thinning	LP	1	1976-29,31	.689	.086
Skyline harvest	Mixed	1	1976-14,18,19,20,21,22,25,26	.673	.036
Helicopter harvest	Mixed	1	1976-35,36,37,38	.631	.048

Effect of Lopping

The effect of lopping was evaluated by combining bulk depths determined before and after lopping, as a data pair for each study area and computing a linear regression constrained through the origin. The resulting equation is plotted over the scatter diagram shown in figure 6. Similarly, the data from all precommercial thinning areas were combined for regression (as shown in fig. 7). The quality of the relationships expressed by "s" values of 0.91 and 0.69, respectively, was good. Note that the ratio of the regression coefficients in table 3 for lopped and unlopped high-lead harvest debris (3.60/4.60 = 0.78) is quite close to our result of 0.83 (fig. 6).

HAZARD Model Application

To illustrate how this study has been utilized, sample printouts of fuel inputs (fig. 8) and fire behavior predictions (fig. 9) are shown for the slash HAZARD model now in use by USDA Forest Service Northern Region. This model affords managers the opportunity to assess the fire implications of tree cutting activities before debris is put on the ground. The fuel loadings required to run the HAZARD model are generated from tree inventories processed through a debris prediction model.[5] The debris prediction model provides total potential debris for all trees on a site. Managers then tailor the total potential debris to specific cutting prescriptions and submit the data for processing by the HAZARD model. To ease checking of the transferred data, the HAZARD model prints out the input data (fig. 8).

[5] See footnote 4.

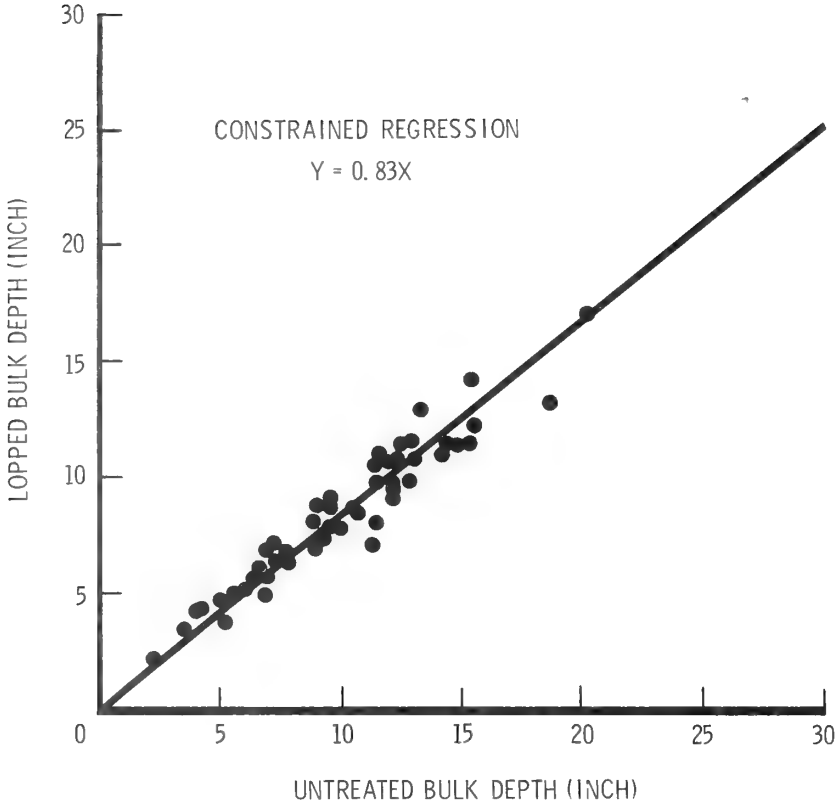


Figure 6.--Bulk depth of lopped slash as a function of bulk depth of unlopped slash for all timber harvest conditions.

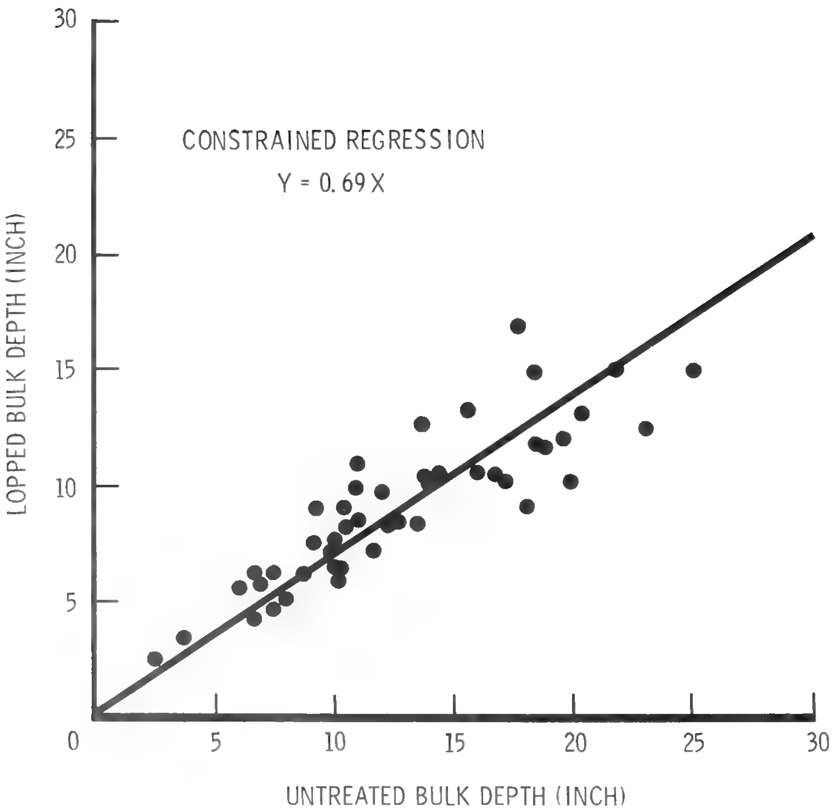


Figure 7.--Bulk depth of lopped slash as a function of bulk depth of unlopped slash for precommercial thinning.

ACTIVITY FUEL FIRE HAZARD ASSESSMENT

INPUT SUBMITTED BY..........

OUTPUT CHECKED BY..........

EXAMPLE INPUT/OUTPUT FOR HAZARD PROGRAM

DATE..........

DEBRIS-PREDICTION INPUT DATA ...

SIZE	SPECIES	LOADING (T/A) BY DBH CLASS 0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-11	11-13	13-15	15-17	17-19	19-25	25-30	30+
-3IN	GF	.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.40	3.00	3.20	.99	1.90	1.00	0.00	0.00
3+IN	GF	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.88	.81	.47	.11	.15	.08	0.00	0.00
CULL	GF	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.70	2.60	3.10	1.00	8.60	6.10	0.00	0.00
-3IN	WL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.70	0.00	.72	0.00	0.00	0.00	0.00
3+IN	WL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.70	0.00	.17	0.00	0.00	0.00	0.00
CULL	WL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.90	0.00	.87	0.00	0.00	0.00	0.00
-3IN	ES	.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.87	0.00	0.00	0.00	0.00
3+IN	ES	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.10	0.00	0.00	0.00	0.00
CULL	BKG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

ACTIVITY-PRODUCED FUELS ... 3 IN AND LESS = 15.9 ... OVER 3 IN = 31.5 ... TOTAL = 47.4

AVG FUEL DEPTH, FT	NUMBER OF WINTERS 1	2	3	4	5
ORIGINAL CONDITION	1.12	1.12	1.12	.96	.81
LOPPED TO 2-FT STD	.94	.94	.94	.82	.69

DOWN-WOODY INVENTORY ...

	LOADING IN TONS/ACRE 1 HR	10HR	100H	3-5	6-9	1020	20 +		
DOWN SOUND	.5	1.0	1.5	3.0	5.0	5.0	2.5	3 IN AND LESS = 3.0 ...	TOTAL = 18.5
DOWN ROTTEN				0.0	0.0	0.0	0.0	...	TOTAL = 0.0

OTHER INPUT DATA ...

NOMINAL GRASS LOADING = 0.0 MEASURED DUFF LOADING = 10.0 AVERAGE SLOPE (PERCENT) = 40

ACTIVITY ... GROUND-LEAD TIMBER HARVEST UTILIZATION STANDARD = 6.0 INCH TOP RUN 14 NOV 77

Figure 8.--Sample printout of fuel inputs as produced by HAZARD program.

EXAMPLE INPUT/OUTPUT FOR HAZARD PROGRAM
ORIGINAL CONDITION
POTENTIAL FIRE BEHAVIOR FOR SEVERELY-DRY CONDITIONS-
(ONE-HOUR TIMELAG FUEL MOISTURE CONTENT = 5 PERCENT)

QUANTITY ASSESSED	20-FT. WIND MI/H	SLASH AGE IN NUMBER OF WINTERS 1	3	5
....	0	4	3	1
HEAD FIRE	5	7	5	3
SPREAD RATE	10	12	8	4
CHAINS/HOUR	15	19	13	6
....	20	27	18	8
....	0	15	11	6
PERIMETER	5	24	17	10
GROWTH RATE	10	36	24	13
CHAINS/HOUR	15	47	31	16
....	20	57	37	17
....	0	2	1	0
BURNED AREA	5	5	2	1
AFTER 1 HOUR	10	11	5	1
BURN, ACRES	15	20	9	2
....	20	29	12	3
....	0	6	5	3
HEAD FIRE	5	9	7	5
FLAME LENGTH	10	11	8	6
IN FEET	15	14	10	7
....	20	16	12	8
....	0	47	31	19
CROWN SCORCH	5	65	41	22
HEIGHT IN FT	10	76	43	18
BY HEAD FIRE	15	82	42	16
....	20	86	42	14
....	0	324	176	81
INTENSITY AT	5	600	335	158
HEAD OF FIRE	10	1081	584	254
(BTU/SEC/FT)	15	1688	885	358
....	20	2395	1224	468

RESIDUAL FIRE FROM BURNOUT OF LARGER FUELS (AND DUFF)

HEAT LOAD (BTU/SQFT)	16439	15202	14344
BURN TIME (MINUTES)	69	69	69

GRD. LEAD HARVEST UTL. STD. 6.0 IN RUN 14 NOV 77

Figure 9.--Sample printout of fire behavior predictions by HAZARD program, based on fuel inputs shown in figure 8.

Fire behavior predictions are furnished in the same format for unlopped and lopped debris (as shown in fig. 9). A further discussion of model output and a guide to interpretation of the fire behavior numbers are in the Northern Region's Users' Guide.[6]

Fuel Bed Depth Prediction

To predict fuel bed depth, predictions of slash in tons per acre are converted to number of 1/4- to 1-inch intercepts through two manipulations. First, weight per unit area is converted to number of 1/4- to 1-inch intercepts by species, using a constant multiplier that is inversely proportional to the product of wood density of the 1/4- to 1-inch pieces and their mean square diameter (Brown 1974). Table 5 gives the conversion factors for 11 western conifer species.

Table 5.--*Factors for converting from 1/4- to 1-inch size class fuel loading to "expected number of intercepts per foot of random transect perpendicular to the ground" for 1/4- to 1-inch size class limb wood of different species*

Species of tree	Factor for tons/acre	Factor for lb/ft^2
Ponderosa pine	0.4309	9.39
Lodgepole pine	.5871	12.79
Western larch	.4382	9.55
Douglas-fir	.5608	12.22
Grand fir	.7295	15.90
Subalpine fir	.5784	12.60
Western redcedar	.6400	13.94
Western white pine	.5258	11.46
Western hemlock	.5950	12.96
Engelmann spruce	.7089	15.45
Whitebark pine	.5258	11.46

Next, number of intercepts are combined for different species. Equations have been given that relate bulk depth to the count of 1/4- to 1-inch fuel intercepts in two crossed, 2-foot vertical planes (this relationship is the same as that for a randomly placed single 4-foot vertical plane). The equations for the pines and for other conifers are different, so in some cases a method of combining them is necessary.

The depth prediction equation can be written for slash of one species type as:

$$\delta_o = a\sqrt{x}$$

where

δ_o = initial bulk depth

x = expected number of intercepts of 1/4- to 1-inch fuel particles in a randomly placed 1-foot vertical plane.

[6]See footnote 3.

The quantity x is proportional to the average loading on the site of 1/4- to 1-inch fuel pieces. When only pines are present in the fuel bed, or when none are present, this formula provides a prediction of fuel bed depth for fire modeling. But when both types are present, the mixed species fuel bed depth will contain contributions for both types. The model for mixed type fuel bed depths used in the HAZARD model is as follows:

Let x_1 = expected 1/4- to 1-intercept count per foot for pine types,

and x_2 = expected 1/4- to 1-intercept count per foot for other types.

If the two types are randomly distributed over the site, then the fraction of the total 1/4- to 1-inch size class loading that is pine type should be (ignoring particle density differences) f_1, where

$$f_1 = x_1/(x_1 + x_2)$$

and the fraction for other types is f_2, where

$$f_2 = x_2/(x_1 + x_2) = 1 - f_1.$$

Now, if the two types were segregated on the site, so that a fraction f_1 of the site area would be covered by pine species and f_2 by others, the expected intercept count *in* the pine-covered area would be x_1/f_1 and the bulk depth in the pine-covered area would be

$$\delta_o^{(1)} = a\sqrt{x_1/f_1}.$$

Similarly, the bulk depth of the other fraction of the area would be

$$\delta_o^{(2)} = a_2\sqrt{x_2/f_2}.$$

On such a segregated site, the *average* bulk depth would be $\overline{\delta}_o$, where

$$\overline{\delta}_o = f_1\delta_o^{(1)} + f_2\delta_o^{(2)}.$$

We take this latter expression to be the average fuel bed depth for the mixed type situation. This equation can be rewritten by substituting for the f and δ_o values to give

$$\overline{\delta}_o = (a_1x_1 + a_2x_2)/\sqrt{x_1 + x_2}.$$

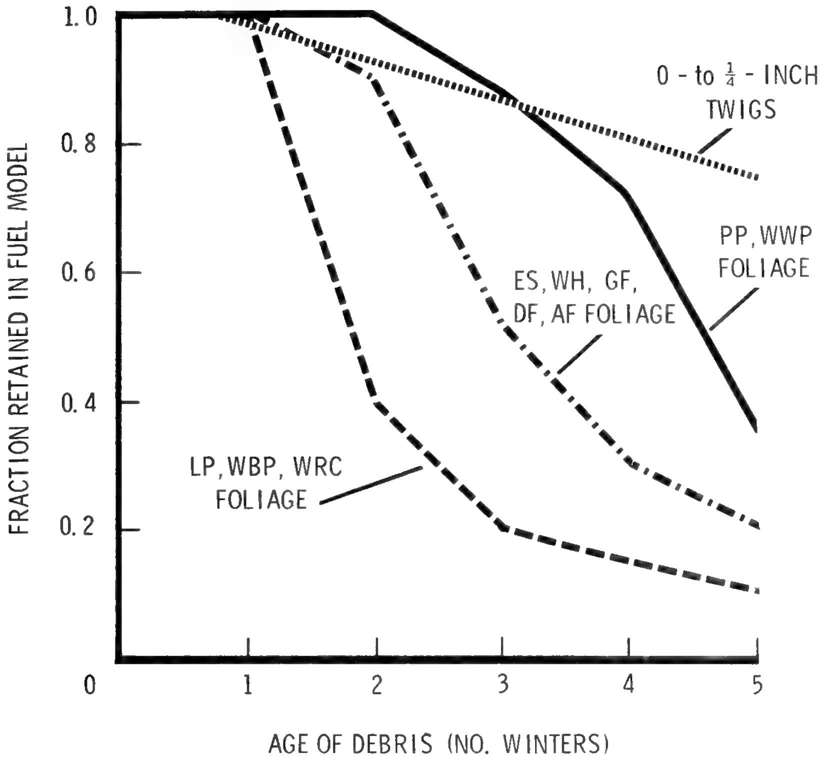
Other factors that affect initial fuel bed depth are reflected in this formula by changing the values of a_1 and a_2 in accordance with the results discussed earlier (fig. 4).

Foliage Loss and Settling

The early effects of aging on debris fuels are settling of the fuel bed and loss of foliage and fine twigs to the forest floor. For modeling fire behavior in slash, it is necessary to quantify rate of settling and the loss of foliage and fine twigs. To operate the HAZARD model, data from Olson and Fahnestock (1955), Fahnestock and Dieterich (1962), Steele (1960), Wagener and Offord (1972), and Brown (1970a) were integrated to describe loss of material (fig. 10). Not all foliage that drops from the branches was excluded from the fuel complex because some foliage remaining in the litter layer and suspended as mats in the slash is still available as fuel for a surface fire.

Settling of slash was modeled as a reduction in depth using table 3, Fahnestock and Dieterich (1962), and Kiil (1968). This study, together with others cited, permitted construction of a settling model adequate for hazard appraisal (fig. 11).

Figure 10.--Reduction of quantity of foliage and small twigs for modeling fire behavior in slash. Not all foliage detached from limbs is lost from fuel available to spread fire.



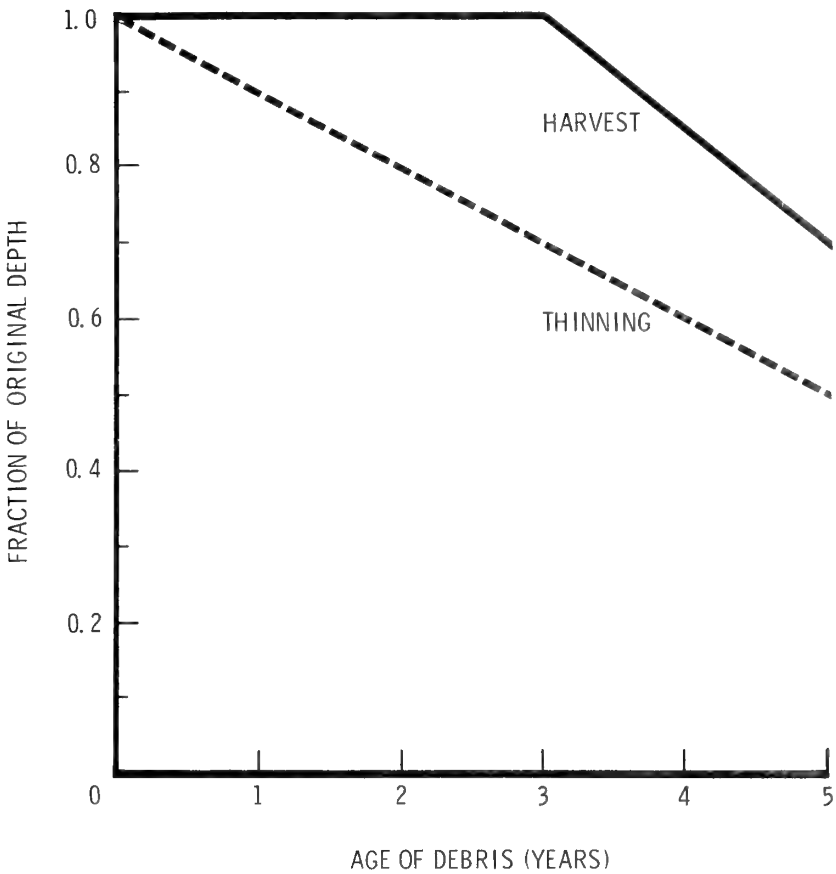


Figure 11.--Settling of slash expressed as a function of the original depth over time for harvesting and precommercial thinning slash.

SUMMARY

To aid in modeling fire behavior for appraisal of slash hazard, equations were developed for predicting fuel bed depth from the loading of 1/4- to 1-inch fuels. The depth equations differed among precommercial thinning, ground-lead harvesting, and high-lead harvesting systems and between pines and other conifers. Settling of slash with age was weakly discerned; however, our findings, together with others, permitted inference of a rough aging model that distinguishes between harvesting and precommercial thinning.

Depth of lopped slash was strongly related to depth of unlopped slash. A strong relationship was also developed between the "bulk depth," useful in fire behavior modeling, and the "high intercept" depth that is easily measured in the field. The influence of merchantable tip diameter on slash depth was evident, although it was not quantified. Accuracy of the depth relationships is probably adequate for most tree cutting activities in western mountainous areas, except perhaps west side slopes along the Pacific Coast. Here the large trees and methods of logging may result in depth/load relationships different from ours. Depth predictions should be verified in the Pacific Coast mountains before modeling fire behavior in slash.

When predictions of fuel depth are coupled with predictions of slash loading (by size class) from tree inventories, the depth models presented here allow prediction of fire behavior before the slash is created. Hopefully, this information will aid in timber sale planning and in management of slash fuels.

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Albini, Frank A., and James K. Brown.
1978. Predicting slash depth for fire modeling. USDA For. Serv. Res. Pap. INT-206, 22 p. Intermountain Forest and Range Experiment Station, Ogden, Utah 84401.

Development of equations for predicting fuel bed depth (called "bulk depth" herein) appropriate for modeling fire behavior in slash is described.

Models for settling of slash, retention of foliage and fine twigs, and species mixing, useful in preparing data for fire models, are presented. Application of the models in a slash hazard appraisal computer program is illustrated.

KEYWORDS: slash, fire behavior modeling, fuel compactness.

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Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field programs and research work units are maintained in:

- Billings, Montana
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